

A NEW OPTIMAL DESIGN APPROACH FOR PLATE-FIN HEAT
EXCHANGERS BY EVOLUTIONARY COMPUTATION

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To my beloved mother and father

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ABSTRACT

Plate-fin heat exchangers (PFHEs) are extensively implemented in practical applications due to their superior compactness and comparatively good heat transfer rate. Nevertheless, the desired high performance and relatively low weight is connected to high pressure drops that consequently result in additional costs. Hence, the design task of PFHEs for industrial applications is an intricate process. To overcome the existing difficulties, this research presents a novel evolutionary-based approach for design optimization of PFHEs based on variable operating conditions instead of the conventional constant heat duty over the working period of the heat exchangers. To find the best suited evolutionary algorithm (EA) for the problem at hand, various widely used EAs are modified and tested on several practical problems. Moreover, since the heat exchanger design optimization is a highly constrained problem and the EAs are not equipped with constraint handling capabilities, conventional external strategies such as penalty function methods have been employed for this problem. The fine-tuning of the penalty parameters have been a drawback of using these methods, therefore a novel feasibility-based ranking strategy is proposed and utilized in the existing EAs. Using the proposed constrained EAs, the design of the PFHEs is presented based on entropy generation minimization (EGM) and economic considerations. Cross-flow PFHEs with offset strip fins on both sides are considered while $\varepsilon - NTU$ method and the correlations available in the literature are employed for rating the heat exchangers. Illustrative case studies from literature are considered to show the efficiency and the accuracy of the proposed methods. The results of numerical tests show that the proposed approach finds the optimal design of PFHEs with superior accuracy and success rate in comparison with the available solutions in the literature.

ABSTRAK

Alat penukar haba plat bersirip (PFHEs) digunakan secara meluas di dalam industri kerana ia padat dan kecekapan pemindahan habanya adalah tinggi. Walau bagaimanapun, kecekapan tinggi dan ringan itu menyebabkan kejatuhan tekanan yang besar dan harganya meningkat. Oleh itu, proses rekabentuk industri PFHE ini adalah mencabar. Untuk mengatasinya, penyelidikan ini memaparkan suatu kaedah yang baru berasaskan pendekatan evolusi dalam pengoptimuman rekabentuk PFHE. Strategi rekabentuk baru ini mengesyorkan satu keadaan berasaskan keadaan kerja yang berubah – ubah dan bukan hanya pada pembebanan terma malar yang lazim dilakukan dalam rekabentuk alat penukar haba. Untuk mencari algoritma evolusi (EA) yang terbaik, beberapa EA yang digunakan dengan meluas telah diubahsuai dan diuji terhadap beberapa masalah praktikal. Di samping itu, disebabkan pengoptimuman rekabentuk alat penukar haba biasanya merupakan masalah pengoptimuman terkekang ketat dan EA tidak mampu mengendalikan hal tersebut, maka strategi luaran yang lazim seperti kaedah fungsi denda digunakan pada masalah ini. Permurnian parameter penalti ini pula mempunyai kelemahan tersendiri. Oleh itu, strategi berasaskan pemangkatan kebolehan yang baru dipadankan dengan EA yang sedia ada. Dengan menggunakan EA terkekang ini, rekabentuk PFHE diajukan berasaskan proses meminimuman entropi terjana (EGM) dan juga pertimbangan ekonomi. PFHE aliran lintang dengan sirip teroffset pada kedua sisi plat diambilkira. PFHE aliran lintang dengan sirip teroffset pada kedua sisi plat diambilkira. Dalam pada itu kaedah ϵ – NTU serta persamaan sekaitan yang terdapat di dalam literatur digunapakai untuk menaksir prestasi alat penukar haba. Beberapa kajian kes dari literatur telah dipertimbangkan bagi menunjukkan kecekapan dan kemampuan kaedah yang disyorkan ini. Hasil ujian berangka menunjukkan pendekatan kaedah baru ini menyediakan rekabentuk optimal PFHE dengan kejutuan dan kadar kejayaan yang tinggi berbanding dengan penyelesaian sedia ada yang terdapat di dalam literatur.

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LIST OF ABBREVIATIONS

CHE	-	Compact heat exchanger
CICA	-	Constrained imperialist competitive algorithm
EA	-	Evolutionary algorithm
GA	-	Genetic algorithm
GAHPSO	-	The hybrid of genetic algorithm and particle swarm optimization
HS	-	Harmony search algorithm
HMCR	-	Harmony memory considering rate
HMS	-	Harmony memory size
ICA	-	Imperialist competitive algorithm
LA	-	Learning automata
LAPSO	-	Learning automata based particle swarm optimization
NTU	-	Number of transfer units
PAR	-	Pitch adjusting rate
PFHE	-	Plate-fin heat exchanger
PSO	-	Particle swarm optimization
TAC	-	Total annual cost (\$/year)

LIST OF SYMBOLS

A, A_{HT}	-	Heat exchanger surface area (m^2)
A_f	-	Annual coefficient factor
A_{ff}	-	Free flow area (m^2)
b_w	-	Pitch adjusting bandwidth
C	-	Heat capacity rate (W/K)
C_A	-	Cost per unit area ($\$/m^2$)
C_{in}	-	Initial cost ($\$/year$)
C_{op}	-	Operating cost($\$$)
C_r	-	C_{min}/C_{max}
D_h	-	Hydraulic diameter (m)
f	-	Friction factor
$f(X)$	-	Objective function
$g(X)$	-	Constraint function
G	-	Mass flow velocity (kg/m^2s)
h	-	Convective heat transfer coefficient (W/m^2K)
H	-	Height of fin (m)
j	-	Colburn factor
K_{el}	-	Electricity price ($\$/MWh$)
l	-	Lance length of the fin (m)
L	-	Heat exchanger length (m)
m	-	Mass flow rate (kg/s)
n	-	Fin frequency (fins per meter)
n_1	-	Exponent of non-linear increase with area increase
N_a, N_b	-	Number of fin layers for fluid a and b
N_s	-	number of entropy generation units

N_{imp}	-	Number of imperialists in ICA
N_{rg}	-	The regrouping iteration period
N_{FS}	-	Number of feasible solutions
P	-	Pressure(N/m^2)
pc	-	Crossover probability
P_g	-	Best global particle in PSO
P_i	-	Best local particle in PSO
pm	-	Mutation probability
Pr	-	Prandtl number
Q	-	Rate of heat transfer(W)
r	-	Interest rate
Re	-	Reynolds number
R	-	Penalty parameter
S	-	Entropy generation rate
t	-	Fin thickness (m)
T	-	Temperature (K)
U	-	Overall heat transfer coefficient
V	-	Velocity of particles in PSO
x	-	A decision variable
X	-	A possible solution in evolutionary algorithms
y	-	Depreciation time
β	-	The assimilation control parameter
ε	-	Effectiveness
η	-	Efficiency of the pump or fan
μ	-	Viscosity (kg/(s.m))
ρ	-	Density (kg/m ³)
τ	-	Hours of operation
$\phi()$	-	Penalty function
ΔP	-	Pressure drop (N/m ²)

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CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, an introduction to the problem at hand is presented that includes an overview of the plate-fin heat exchangers (PFHEs) and their importance along with the background of the problem, problem statement, research objectives, significance of the study, scope of the study and thesis organization.

Generally, heat exchangers are defined as devices that facilitate the heat transfer between two streams of flows. Heat exchangers are an essential element in many areas such as air conditioning, waste heat recovery, power generation etc. Among various types of heat exchangers, compact heat exchangers (CHEs) distinguish themselves by their high “area density”, the ratio of heat transfer area to the heat exchanger volume, that results in lower weight and volume.

These characteristics along with their high-heat transfer performance make CHEs more preferable in many industrial applications because of the savings in the material and the required space for a specific heat duty. The latter is especially important in applications, such as concentrated solar power systems (Li et al., 2011), where the space restrictions are vital and CHEs are one of the possible solutions for these types of applications. A specific definition of CHEs was presented by (Shah and Sekulić, 2007).

An area density of over $700 \text{ m}^2/\text{m}^3$ and $400 \text{ m}^2/\text{m}^3$ was introduced as the criterion for the applications that make use of at least one stream of gas and others respectively. As a typical heat exchanger, the area density of shell-and-tube heat exchangers is less than $100 \text{ m}^2/\text{m}^3$ for fluid sides with plain tubes and approximately 2-3 times higher with high-fin-density low-finned tubing.

Some types of CHEs have been widely employed in industrial applications for many decades while some other types are relatively new in the market and there are still new patents that are being tested in the laboratories. However, Commercial CHEs are typically fin-and-tube or plate-fin designs. Between these two types, a design based on the latter called plate fin heat exchanger (PFHE) is widely used in gas-gas applications such as automobile, chemical and petrochemical processes, cryogenics and aerospace.

A PFHE consists of several corrugated sheets that are separated by parting layers and are enclosed by side bars to form a finned chamber (Shah and Sekulić, 2007, Kays and London, 1984). The whole system, i.e. the fins and parting layers are brazed in a vacuum furnace to ensure that a single rigid core is formed. A drawing of a typical brazed Aluminum PFHE is presented in Figure 1.1. Since the arrangement of fins can be easily changed, a PFHE has the ability to work in cross-flow, counter-flow, cross-counter flow and co-current flow layouts. A simple cross-flow arrangement is usually employed in low or moderate heat transfer duties. A PFHE is adaptable to any combination of gas, liquid, and two-phase fluids (air-to-air, air-to-liquid and liquid-to-air). Different types of fins, including wavy, offset-strip, louver, perforated and pin fins (Kays and London, 1984) can be implemented on a PFHE for enhancing the heat transfer. Despite their superiority in term of achieving a high thermal performance, plate-fin heat exchangers show large pressure drops consequently which leads to higher operational costs. As a result, for practical applications and based on the required constraints, PFHEs have to be designed to present a trade-off between their high thermal performance and the induced additional costs resulted from the increase in pressure drops.

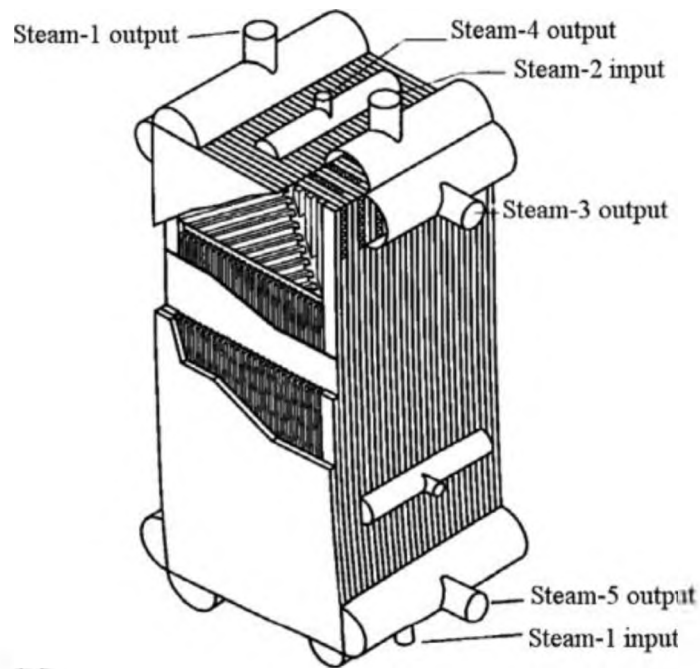


Figure 1.1: Typical multi-stream plate-fin heat exchanger

1.2 Background of the problem

For achieving a practical design of PFHEs, commonly, a trial-and-error process is performed for finding the geometrical parameters in a way that all necessary requirements are attained. These requirements are generally a specific heat transfer rate or predefined exit temperatures. Additionally, this process usually involves taking into account specific constraints such as maximum allowable pressure drops, size and weight limits. Moreover, specific optimization objectives should be considered by the designer prior to the design process. As an example, considering the cost considerations, a lower capital cost can be generally achieved by smaller heat transfer area. This in turn can be attained by adopting higher heat transfer coefficients that correspond to higher flow velocities. However, shifting the design toward higher flow velocities would ultimately result in higher pressure drops and therefore the operational costs of the heat exchanger would increase (Jia and Sunden, 2003; Muralikrishna and Shenoy, 2000; Nasr and Polley, 2000; Shah and

Sekulić, 2003; Wang and Sundén, 2001). The variation of total, area and power costs with flow velocity is demonstrated in Figure 1.2. The initial cost (capital cost) is mainly associated with the heat transfer area while operation cost is essentially the required power cost for overcoming the pressure drops.

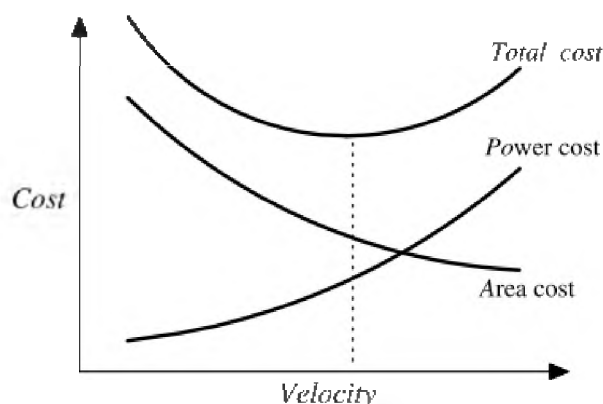


Figure 1.2: Optimization of a heat exchanger from economic point of view.

Moreover, the growing need for more efficient thermal systems and conserving energy resources has led to a completely new point of view in thermodynamic analysis and optimization of systems. The new methodology that simultaneously makes use of both first and second laws of thermodynamics is called exergy analysis and its optimization term is known as entropy generation minimization (EGM). Exergy of a system accounts for the maximum work it can produce theoretically. In contrast to energy that is never destroyed during a process, exergy is always destroyed when a process involves irreversibility as a result of temperature difference, friction and etc. The amount of destroyed exergy is proportionate to the amount of entropy generation. The EGM method, as illustrated in Figure 1.3 occurs in the interface of heat transfer, engineering thermodynamics and fluid mechanics.

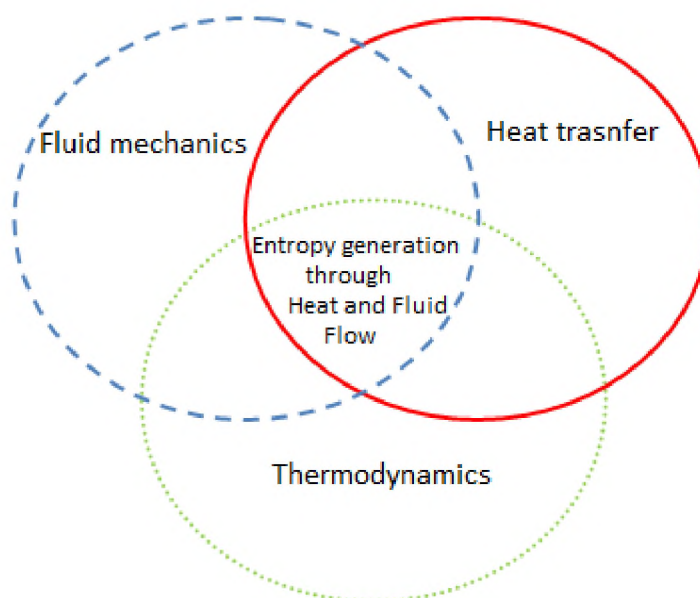


Figure 1.3: The interdisciplinary field covered by the method of entropy generation minimization.

The EGM method was first introduced by Bejan (Bejan, 1977) where the design of a gas-to-air heat exchanger for minimum irreversibility was presented. Considering a constant number of entropy generation units, this study also presented the design of a regenerative heat exchanger for minimum heat transfer area.

Considering the various objectives, ahead of the design procedure, the optimization objectives should be considered carefully by the designer. Due to the complexity of the PFHEs design process, it has remained an active field of research, and various studies have proposed different strategies ranging from traditional mathematical formulations (Reneaume and Niclout, 2003, Reneaume et al., 2000, Reneaume and Niclout, 2001) to artificial neural networks (Jia and Sunden, 2003) and evolutionary methods (Ahmadi et al., 2011, Sanaye and Hajabdollahi, 2010, Rao and Patel, 2010, Peng et al., 2010, Mishra et al., 2009, Mishra and Das, 2009, Xie et al., 2008, Peng and Ling, 2008, Guo et al., 2008, Xie and Wang, 2006).

Evolutionary algorithms (EAs) seek an optimum solution for an optimization problem by approaches inspired by evolution process (Zang et al., 2010). These approaches are generally appropriate for different types of problems since they are

not required to make any assumption about the problem at hand. A great advantageous of EAs is that no information of derivatives is required. The performance of EAs is not dependant on the initial values of decision variables that could be essential in traditional optimization approaches. As a result of these characteristics, EAs have been effectively employed in diverse domains including operations research, scheduling, marketing, chemistry, robotics, art, social science, physics, and biology. Moreover, EAs have been demonstrating their effectiveness and strength in design and optimization of thermal systems that include handling several decision variables and constraints at the same time. A comprehensive review of the application of these methods in thermal systems design can be found in (Gosselin et al., 2009).

1.3 Problem statement

Compact heat exchangers have a significant role in different aspects of industry due to their high performance and relatively small weight and size. Among different types of compact heat exchangers, plate-fin heat exchangers (PFHE) are the most popular one. However, the design of these heat devices has been always a challenging task since a large number of variables and constraints should be considered at the same time. In the practical applications, a heat exchanger is usually needed to be designed for a specified heat duty and working conditions. In this case, the main decision variables are the geometrical characteristics of a PFHE. These design variables should be chosen in a way that the desired heat duty is achieved while the specific constraints, such as size or pressure drops limitations are satisfied. Moreover, the growing prices of energy and material have strengthened the need for optimum designs based on cost minimization. A design, not only should satisfy all the requirements and constraints, but also should provide a near-optimum solution. In addition, any heat device could be also considered an individual in the whole thermal system; therefore, second-law based optimization could also be important. The complicated task of PFHE design could be faced by

employing evolutionary-based approaches. Many evolutionary algorithms have been presented in recent years and shown great performance in various engineering applications (Mahdavi et al., 2007, Atashpaz-Gargari and Lucas, 2007, Kennedy and Eberhart, 1995, Geem et al., 2001b, Rezaei et al., 2012, Nicknam and Hosseini, 2012, Shariatkhah et al., 2012, Sirjani et al., 2012); however, there has not been much effort in modifying and employing them for this task. The EAs are problem dependant and there is not a single algorithm that could be introduced to outperform all the others in all engineering applications.

Moreover, the EAs are naturally introduced for unconstrained applications and in order to make them compatible with the highly constrained PFHE design, external approaches should be implemented. Static penalty functions have been extensively utilized for many engineering application including thermal system's design optimizations (Pacheco-Vega et al., 1998, Tayal et al., 1999, Pacheco-Vega et al., 2003). However, this method induces additional parameters that should be carefully tuned for achieving reasonable performances. The fine-tuning of the penalty parameters has been a drawback of using these methods, therefore, a more efficient and user-friendly constraint handling strategy is needed to be present and employed for evolutionary design approach of PFHEs.

Additionally, the available works in the literature have neglected the fact that in many engineering application the thermal device is not working for a constant heat duty and the working conditions can vary in time. The study aims to present a framework for these problems by considering multi-stage designs.

1.4 Research Goal

The main research goal of this study is to present a novel evolutionary-based approach for design optimization of PFHEs. The new design strategy is based on variable operating conditions instead of the conventional constant heat duty over the

working period of the heat exchangers and a novel feasibility-based ranking constraint handling strategy. Moreover, the study aims at investigating the performance of the newly introduced EAs on the PFHE design problem and to find the best suited one.

1.5 Research objectives

Overall, the followings are the main objectives of this study. Hence, the followings are the research questions that will be addressed in this study.

- 1) How the design of PFHEs is affected by variable operating conditions instead of the conventional constant ones?
- 2) How the difficulties of fine-tuning of penalty parameters can be solved?
- 3) How the best suited evolutionary algorithm for solving PFHE design optimization could be determined?

To achieve the aim and for answering the above questions, the following research objectives are formulated.

- 1) To develop a novel multi-stage design strategy for compact heat exchangers that could be employed in other types of heat exchangers as well.
- 2) To establish various design points for PFHEs including second-law based, economic-based, etc.
- 3) To develop and apply a parameter-free constraint handling strategy for eliminating the difficulties of the existing penalty function methods.
- 4) To improve the performance of the existing evolutionary algorithms and present their application in thermal systems, which is scarce.

1.6 Significance of the study

Unlike the previous studies on PFHE design, this research presents the design optimizations based on variable operating conditions, which are more consistent with the real-world application of PFHEs. The presented ranking-based constraint handling approach is more efficient and user-friendly when compared to the conventional penalty function methods. Moreover, since the application of the newly introduced evolutionary algorithms is scarce in the thermal engineering problems, this study also provides a better understanding of these algorithms.

1.7 Scope of the study

The main aim of this study is to present a robust evolutionary-based design approach for cross-flow plate-fin heat exchangers for achieving optimum configurations considering various objective functions. These objective functions include achieving minimum total annual cost and minimum number of entropy generation units. The cost calculation is made based on the available works in the literature. The electricity cost is assumed to be constant throughout the working period of the heat exchangers though an inflation rate is employed. The entropy generation is calculated based on methodology of Bejan (2002). The thermal modeling is based on the available correlations in the literature and this study is not to explore the empirical aspects of heat exchanger design. In the thermal analysis, the PFHE is modeled under steady-state condition. Moreover, the variations of thermal characteristics of working fluids with temperature are not considered. The fouling is not considered in thermal modeling because it has a negligible effect in gas-gas applications.

1.8 Thesis organization

The thesis is organized as follows. In the first chapter an introduction to the existing problems in plate-fin heat exchanger design optimization are described and the goals and objectives of the study are presented accordingly. To understand the background of the problem, a comprehensive exploration on the existing literature is provided in Chapter 2. A comprehensive background of the existing approaches for PFHE design optimization is presented along with a literature review on the evolutionary algorithms. The most dominant evolutionary algorithms along with their advantageous and disadvantageous are presented in this chapter. Chapter 2 is continued with a comprehensive literature on the constraint handling strategies that have been used for solving constrained optimization problems when they are solved with evolutionary algorithms. Based on existing gaps in the literature and to fulfill the objectives of the study the research methodology of this study is presented in detail in Chapter 3. The thermal modeling of the heat exchanger, which is essential for starting the optimization process through evolutionary computation, is presented at first. Afterwards the objectives of the optimization problems are described. The total annual cost and number of entropy generation units are the main objectives of the optimization. The evolutionary-based design framework including decision variables and problem representation is presented subsequently. Next, the proposed constraint handling strategy is described. The proposed strategy solves the existing drawback of the available methods through eliminating the parameter-settings and providing feasible solutions at any condition. The numerical results and the corresponding discussions are presented in Chapter 4. Firstly, the numerical results on several practical case studies from the literature are presented using the methodology presented in Chapter 3, and then based on the attained results and the literature; discussions are made in Section 4.4. The numerical results cover both single- and multi-stage optimization problems (Sections 4.2 and 4.3). Finally, the conclusions and recommendations for the future works are drawn in Chapter 5.